$LiNbO_3$ WAVEGUIDE QUASI-PHASE-MATCHED SUM-FREQUENCY GENERATION INTERFEROMETER DEVICE FOR ULTRAFAST OPTICAL SWITCHING

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1. Introduction

All-optical switching devices are required for future photonic network systems. One of the candidates is devices using quasi-phase-matched (QPM) second-order nonlinear optical interactions in ferroelectric waveguides, which offer advantages of ultrafast response, potentially low switching power, wide wavelength coverage, and integration compatibility.

Switching using phase shift associated with cascaded second-order nonlinear interactions was studied [1],[2], and self switching with kW power was demonstrated in a waveguide interferometer using birefringent phase matching [3]. Gate switching using phase inversion by cascaded sum- and difference- frequency generation (SFG/DFG) was demonstrated in a QPM waveguide with Kerr shutter configuration [4]. Use of signal depletion by QPM-SFG for negative-logic gate switching was demonstrated [5]. Wavelength-conversion-type picosecond switching using a waveguide QPM-SHG/DFG device was demonstrated [6].

In this paper, we propose and demonstrate a waveguide QPM-SFG Mach-Zehnder interferometer device for ultrafast all-optical gate switching. The device is fully integrated, and can perform picosecond positive-logic gate switching with moderate switching power.

2. Working principle and theoretical performance

Fig. 1 illustrates the switch configuration. The device consists of a QPM-SFG section and a π phase shifter (PS) integrated in each arm of a $LiNbO_3$ waveguide Mach-Zehnder (MZ) interferometer. A signal wave of frequency ω_1 (wavelength λ_1) and control pulses of ω_2 ($\neq\omega_1$) (λ_2) are coupled into the input port. The SFG section has a ferroelectric domain inverted grating with a period Λ designed for QPM-SFG ($\omega_3=\omega_1+\omega_2$, λ_3). The QPM period for λ_1, λ_2 in the1.5μm band is around 18μm [7]. Without control pulses, the signal waves transmitted through the both arms interfere destructively at the combining section and the signal is extinct at the output port. When the control pulse turns on, SFG gives rise to signal wave depletion [4],[5] in the SFG arm, and the extinction is violated so that the signal is transmitted. Thus the device serves as a positive-logic optical gate switch.

The nonlinear interaction in the SFG section can be described by the coupled-mode

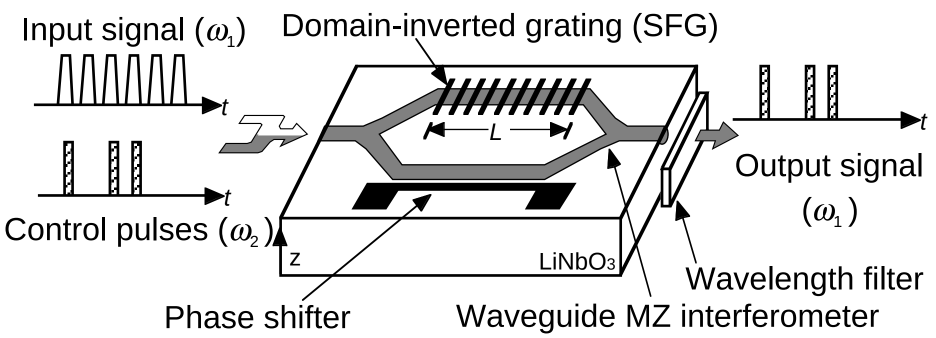

Fig. 1 Integrated $LiNbO_3$ QPM-SFG interferometer device for optical switching.

equations. Assuming that all the waves are CW and the control power is so strong that its depletion can be neglected, the equations under exact QPM can be written as

$$dA_1(z)/dz= -j(\omega_1/\omega_3)\kappa A_2^*A_3(z),\ \ dA_3(z)/dz= -j\kappa A_2A_1(z), \qquad (1)$$

where A_1, A_2, A_3 are the amplitudes of the signal, control and SF waves in the SFG section, and κ the coupling coefficient. The solution for $A_1(z)$ with $A_3(0)=0$ can be written as

$$A_1(z) = A_1(0)\cos\sqrt{(\omega_1/\omega_3)\ \kappa^2A_2^*A_2}\,z. \qquad (2)$$

Eq.(2) describes the signal wave depletion due to SFG. The normalized output signal power of the interferometer with a SFG section of length L and a π PS is given by

$$P_{1\mathrm{out}}/P_{1\mathrm{in}} = \left|\cos\sqrt{(\omega_1/\omega_3)\ \kappa^2L^2P_{2\mathrm{in}}/2} - 1\right|^2 / 4 = \sin^4\left\{(\pi/4)\sqrt{P_{2\mathrm{in}}/P_{\mathrm{C}}}\right\}, \qquad (3)$$

where $P_{1\mathrm{in}}$, $P_{1\mathrm{out}}$ are the input and output signal powers, $P_{2\mathrm{in}}$ is the input control power, and $P_{\mathrm{c}}= (\pi^2/2)(\omega_3/\omega_1)/(\kappa^2L^2)$ the input control power for complete signal depletion in the SFG arm. The 3dB branching loss for the control power is included in Eq.(3). The normalized SFG efficiency is given by κ^2L^2 [7]. With increase of $P_{2\mathrm{in}}$ to P_{c} the transmittance $P_{1\mathrm{out}}/P_{1\mathrm{in}}$ increases to 0.25. With further increase of $P_{2\mathrm{in}}$, DFG takes place to generate phase-inverted signal wave [4], and the transmittance increases up to 1 at $P_{2\mathrm{in}}=4P_{\mathrm{c}}$.

When control pulses with spectral bandwidth wider than the QPM bandwidth is used, the depletion and the transmittance are reduced. The reduction can be interpreted in terms of the walk-off between the control and SF pulses. To avoid such reduction, L should be short, while short L results in large P_{c}. Therefore the switching speed and power must be traded off. Approximate calculation [7] showed that a SFG device of L=5mm can be used for 1ps pulses in 1.5μm band without substantial efficiency reduction. For κ^2L^2～63%/W, the theoretically estimated value for L=5mm [7], the complete depletion power is calculated as P_{C}～16W. In the previous experimental work κ^2L^2～43%/W was obtained [7].

3. Fabrication

We fabricated optical switches having a QPM-SFG section of L=5mm and a thermooptic PS on z-cut $LiNbO_3$ crystal of 0.5mm-thickness. Domain inverted gratings for QPM were fabricated by applying a high-voltage pulse of ~11kV between liquid electrodes on the +z surface with resist gratings and on the bare -z surface. The period and the area of the QPM gratings were 15.0~18.8μm and 5x0.1mm². Fig. 2 shows a microphotograph of a QPM grating with Λ=18μm. Waveguide MZ interferometers were fabricated by proton exchange in benzoic acid at 200ºC for 1.5h using PCVD-SiO_2 mask with 3.3μm-width channel openings patterned by EB-writing and RIE. After mask removal, the sample was thermally annealed at 350ºC for 4h in O_2 atmosphere. Then the waveguide input/output ports were polished. Finally, Ti-film heaters of 200nm-thickness for the PS were fabricated by photolithography and sputter deposition.

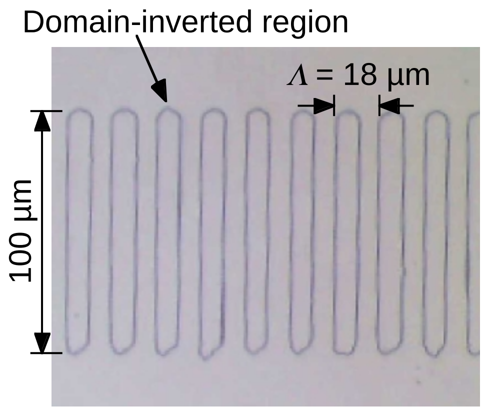

Fig. 2 Domain-inverted grating (visualized by etching).

4. Experiment

As a preliminary test, we measured the characteristics of the MZ interferometer by CW operation. An external cavity tunable LD (λ_1 ~ 1.55μm) was used as a light source. Total throughput of the device (without PS driving) was ~ 10% including a loss at PM-fiber to input port coupling. Comparison with 20% throughput obtained in reference waveguides indicates excess losses of ~ 3dB at the branching/combining sections of the MZ waveguide. The propagation loss of the reference waveguide was ~ 1dB/cm. Fig. 3 shows the dependence of the output power on the PS driving voltage. We obtained an extinction ratio as large as 29dB at the voltage of ~ 10V.

Fig. 4 shows the experimental setup for optical switching. An external-cavity tunable LD was used as a signal source of λ_1 ~ 1.55μm. A DFB-LD was driven by 1GHz sinusoidal wave to generate gain switched pulses. The pulses were compressed by a dispersion compensation fiber, amplified by an Er-doped fiber amplifier, and filtered through a tunable bandpass filter to cut the ASE background. The pulse width was measured as 10ps. The wavelength and bandwidth were λ_2=1.543μm and 0.6nm, respectively. The control pulses and signal wave (CW) were combined by a 3dB fiber coupler and coupled to the input port of the device.

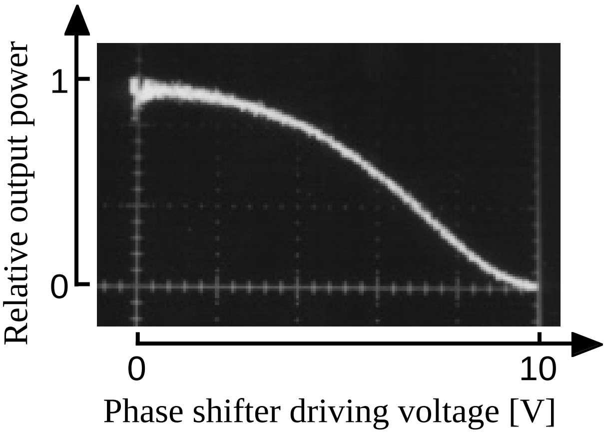

Fig. 3 Dependence of the output power on the PS driving voltage.

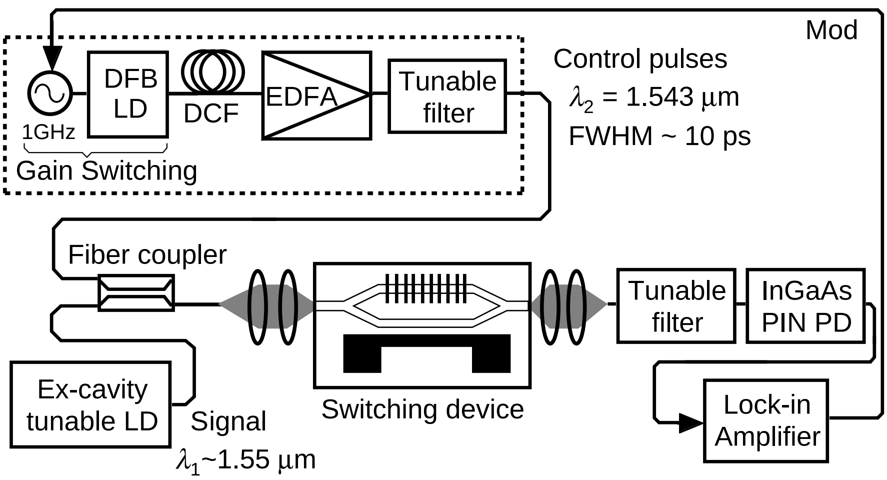

Fig. 4 Experimental setup for optical switching.

In a switch having a grating of Λ=17.0μm, strongest QPM-SFG was observed when the signal was tuned at λ_1=1.553μm (at π PS driving). The QPM bandwidth in terms of the signal wavelength was ~5nm consistent with the theoretical value [7]. The output wave was transmitted through a fiber and a tunable filter to an InGaAs PIN photodiode. In order to detect the output signal switched by the picosecond control pulses of a small duty ratio 1/100, the phase-sensitive detection method was employed. The DFB-LD driving was chopped at 1kHz, and the output signal was measured by using a lock-in amplifier. The filter was tuned first at λ_2 to detect the control pulse burst and calibrate the lock-in phase, and then tuned at λ_1. Without PS driving, the signal depletion was confirmed in the form of negative lock-in amplitudes. When the PS was driven for π phase shift, positive lock-in amplitudes were obtained. No output signal was obtained, when either signal wave or control pulses were turned off or the signal was detuned to outside of the QPM bandwidth.

Fig.5 shows the dependence of normalized output signal power on the control power. The average power of the control pulses was measured at the output port without PS driving, compensated for the 4dB propagation and excess losses, and divided by 1/100 to give the coupled peak power. To give the normalized output signal peak power, the measured lock-in amplitude was divided by the value corresponding to the power transmitted without PS driving and by $1/100\sqrt{2}$ assuming $(10/\sqrt{2})$ps width expected by Eq.(3). In the same figure, the calculated dependence is also plotted with κ^2L^2 as a parameter. The experimental result compares fairly well with the curve for κ^2L^2=40%/W. The signal peak transmittance of 0.024 , well above the extinction revel -29dB=0.0013, was obtained for 6.3W coupled control peak power. These results indicate that the positive-logic gate switching is obtained, although the measurement is not time resolved.

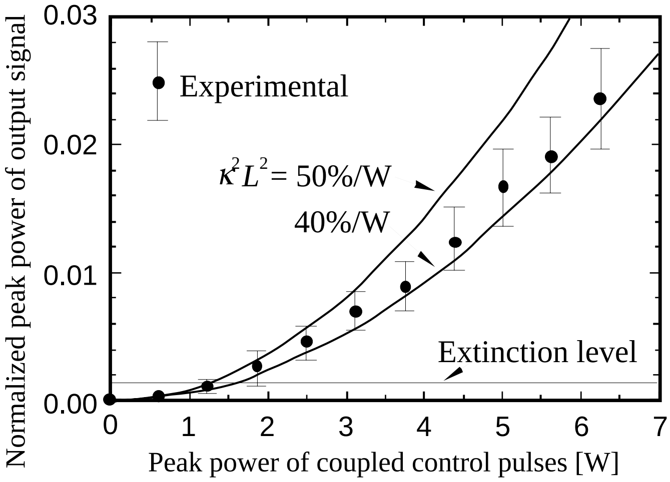

Fig. 5 Dependence of the normalized output signal peak power on the control pulse peak power

5. Conclusion

Picosecond optical gate switching using an integrated $LiNbO_3$ waveguide QPM-SFG interferometer device has been proposed and demonstrated. Experimental work is being continued for improvements of switching efficiency and reduction of the switching power.

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